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Influence of the antecedent long-term precipitations on the initial conditions in a sloping pyroclastic deposit

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Abstract

The hydrological response of a shallow sloping deposit in unsaturated pyroclastic soils is being monitored since 2002. The area is located in Cervinara, Campania Region (Southern Italy), where a catastrophic flowslide occurred on December 16th, 1999, as a consequence of a 2-day cumulative rainfall of 320 mm causing heavy damage and five deaths. The installed devices provide information about rainfall height, soil suction and, recently, also about volumetric water content at several locations and depths along the slope. The huge number and high quality of data allowed to develop a consistent model about the hydrological slope response and particularly to correlate the antecedent long-term precipitations with the soil matric suction at the beginning of a potential triggering rainfall, focusing on the hydrological conditions that establish in the different seasons. In particular, this can help in assessing the likely initial suction values at the time of a potential triggering rainstorm.

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Keywords: Hydrological response; monitoring; unsaturated granular soils; pyroclastic slope

1. Introduction

During the last decades, in Campania (Southern Italy) intense rainfall events triggered flow-like landslides in unsaturated cohesionless pyroclastic sloping covers causing victims and huge economic damages. The return period of such events is about 4 years, as revealed by Table 1 that reports the thirteen main landslides occurred from 1954

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to 2005. In detail: i) eight of them were triggered during Winter; ii) only one event occurred in Spring (the sadly famous Sarno event, May 5th, 1998, that caused 160 victims[1]); iii) four events occurred during Autumn. No relevant landslides were recorded in April, June, July, August and September. This seasonal distribution is not only due to the pluviometric features of the triggering rainstorms (duration, intensity), but also to the unfavourable initial conditions of the covers that are strongly influenced by the previous long-term rainfall history.

Table 1. Main flow-like landslides occurred in Campania Region from 1954 to 2005[2,3].

Site	Month	Day	Year
Gragnano	January	2	1971
Castellammare	January	10	1997
Pimonte	February	17	1963
Mitigliano	February	16	1973
Palma Campania	February	22	1986
Pagani	March	6	1972
Nocera	March	4	2005
Sarno	May	5	1998
Tramonti	October	26	1954
VicoEquense	November	23	1966
Pagani	December	9	1960
Cervinara	December	16	1999
Bracigliano	December	26	2004

The pyroclastic sloping deposits are usually layered. The slope angle is very close to that of the bedrock surface. The thickness of the covers depends on the slope angle, ranging from some decimeters in the uppermost steepest zone (whose inclination is higher than 45°) to more than ten meters at the nearly flat hillfoot[4]. Stability of the steepest areas is assured by soil matric suction, whose regime is strictly related to seasonal climate fluctuation. As a consequence, the probability of slope failure induced by a given storm event changes during the year, being strictly related to the initial soil conditions that are, in turn, determined by the antecedent long-term meteorological variables.

Well aware that field hydrological monitoring is a fundamental tool to better understand the slope response to weather events, since 2002 the research team of the Second University of Naples is being monitoring the seasonal fluctuation of matric suction measured within a shallow sloping deposit in unsaturated pyroclastic soils. The selected area is located in Cervinara, about 50 km North-East of Naples, where on December 16th, 1999, a flowslide was triggered by the most intense 2-day cumulative rainfall recorded in that area (320 mm), killing five people[5]. On November 9th, 2010, a very similar rainstorm (308 mm fallen in two days) was registered in Cervinara but it did not provoke any slope failure. The two opposite effects observed after comparable rainstorms occurred in different periods suggest the key-role of starting conditions on slope response.

After a short description of the monitored site, the paper will report some statistical considerations concerning the field data collected during a 10 years long monitoring period, in order to assess the seasonal influence of antecedent cumulative rainfall on initial conditions.

2. Monitored site

The monitoring station was installed next to the detachment area of the 1999 flowslide. This occurred on a 40° slope, facing North-East at about 560 m a.s.l., located a couple of kilometers upslope the town of Cervinara (Fig. 1a). In the monitored area the pyroclastic cover presents a maximum thickness of about 2.4 m and consists of thin alternating unsaturated layers of pumices and ashes laying upon a fractured calcareous bedrock (Fig. 1b).

The geotechnical properties of such soils have been widely investigated in laboratory[6]. The grain-size distributions of the soils vary from a sandy silt to a sandy gravel. The volcanic materials are characterized by high porosities (55-70%) and quite low values of the soil unit weights (13-16 kN/m^3) due to their nature and their mode of deposition (air-fall). Saturated conductivities range from 9E-07 m/s to 5E-06 m/s but, in unsaturated conditions, they may decrease of more than two order of magnitude. From a mechanical point of view, the soils are characterized by high values of the friction angle (31°-38°) and low to nul values of the effective cohesion. In unsaturated conditions, an apparent cohesion develops due to the presence of matric suction that guarantees the stability of this shallow cover also for slope angles higher than the friction angles of the soils.

The basal surface of the 1999 flowslide was located at a depth of about 1.5-2.0 m[7], i.e. at the base of the most thick ashy layer which is completely cohesionless in saturated condition and has a friction angle, $\varphi' = 38°$, lower than the mean slope angle. This suggests that failure may occur only when the soil is very close to saturation.

Field monitoring of both rainfall and soil matric suction started in 2002[8]. Hourly precipitations were automatically measured by a rain gauge with a sensitivity of 0.2 mm. Suction was measured manually until 2009 with a frequency of about 15 days by means of 18 jet-fill tensiometersequipped with a Bourdon manometer. The tensiometers were installed at different depths within the ashy layers at five different sections along the slope (Fig. 1). An additional automatic monitoring station, constituted by two different nests of sensors, was installed in 2009[9]. Since then suction is being measured by 8 additional jet-fill tensiometers, installed at different depths with a maximum value of 1.7 m. The automatic acquisition and storage of data occurs with a time resolution of two hours. Summing up, the overall equipment (26 tensiometers) covered seven sections: i) 7 tensiometers, in the following indicated as "shallow", were installed at a depth of 60 cm; ii) 8 tensiometers, indicated as "intermediate", were installed at the range of depths 0.90-1.30 m; iii) 11 tensiometers, indicated as "deep", were installed at the range of depths 1.40-2.40. In particular, the deep tensiometers are located at a maximum distance of 50 cm from the bedrock.

The automatic station is also equipped with 7 TDR metallic probes aimed at recording thesoil moisture content. Some of them are located very close to the ceramic tips of the tensiometers(Fig. 1b) in order to couple water content and suction at the same location. In particular, Fig. 2 shows the couples of data collected in the ashes during a two-years long monitoring period (2010-2011): the reported values of saturation degree have been derived by the measured soil moisture assuming a soil porosity equal to 0.70[6]. The observed scattering is likely due to the hysteretic hydraulic behaviour of the soil[10,11,12], which leads to different values of the moisture content for the same suction value, depending on the current wetting or drying path. Fig. 2 also includes the results of some laboratory infiltration tests performed on a small-scale slope reconstituted with the same soil in an instrumented flume[13]: the laboratory and field data have been interpolated with an unique fitting Water Retention Curve.

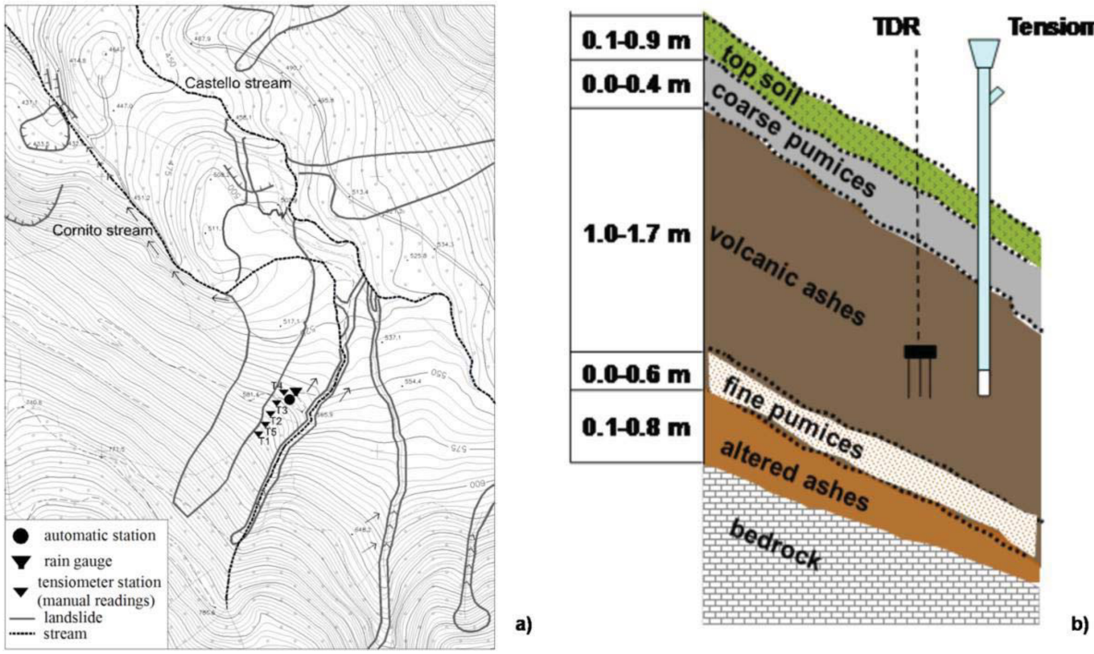

Fig. 1.Monitored site: (a) plan view of the instrumented slope and of landslide occurred in Cervinara on December, 1999[6]; (b) soil stratigraphic profile.

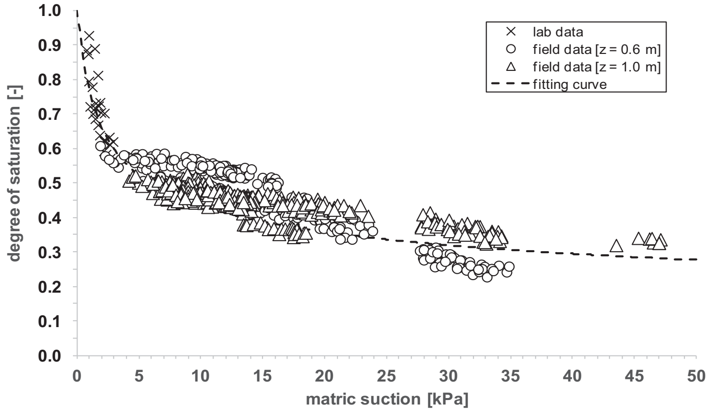

Fig. 2. Water Retention Curve of Cervinara ashes obtained by fitting experimental data coming from field monitoring[10] and laboratory tests[6].

3. Statistical considerations on available data

During the reference period 2002-2011, the annual cumulative rainfall in Cervinara was about 2000 mm on average. Fig. 3a shows the distribution of the mean monthly cumulative rainfall measured at the site and of the mean daily temperature recorded by the nearby Pietrastornina weather station managed by the Civil Protection Agency. The observed monthly rainfall ranges from a minimum value of about 40 mm, in August, to a maximum one of 300 mm, in December (close to that measured on the occasion of the 1999 flowslide). The mean daily temperature goes from a minimum of 6 °C in January, to a maximum of 24 °C, in July and August.

In order to assess the influence of precipitations on the soil matric suction, a detailed statistical analysis of the data has been carried out providing the cumulative frequency distribution of suction for every month. Fig. 3 shows the 25th, 50th and 75th percentiles representative of low, median and high values of suction, while Table 2 summarizes all collected data on a quarterly basis for three ranges of depth.

The annual distribution of the 25th percentile is shown in Fig. 3b. At the shallowest depths, matric suction is lower than 6 kPa in Winter, then it steadily increases of about 1.4 kPa/month in Spring and of about 6.5 kPa/month in Summer, attaining the maximum value of 28 kPa in July. In Autumn, it drops to 6-8 kPa. At the highest depths, suction is lower than that measured at the shallow depths in the time interval December-July, while it is much higher from August to November. This result, observed also in another site in Campania[14], is probably due to the influence of the downward flux at the soil-fractured bedrock interface, which during the dry periods is not balanced by the infiltration from the ground surface[15]. The figure also shows that after the dry Summer period, the lowest suction measured by the deepest sensors is attained with a delay of about three months with respect to the time concerning the shallowest depths (in September). As a likely explanation, notice that the capillary potential gradient and the capability of the soil to retain water increase with suction (that is quite high at the end of Summer), while the hydraulic conductivity decreases with it. Therefore, it's evident that the first and second phenomena, that enhance the infiltration process, prevail over the third one only at the shallowest depths. Concerning the intermediate depths, suction is very close to that measured by the deepest sensors during all the year, with the exception of Autumn when it approaches the values measured by the shallowest sensors. Moreover, after Summer the lowest value is attained with a delay of about one month.

Fig. 3c reports the seasonal trend of the 50th percentile. Such a median value is from about 40% to 60% higher than the 25th percentile. The highest increase is shown by the deepest tensiometers especially in Autumn, when suction reaches its peak value (around 65 kPa in November), in spite of an high cumulative monthly precipitation (284 mm on average). It's worth noting that at the shallow and intermediate depths the trends are very similar to those corresponding to the 25th percentile.

Concerning the 75th percentile, Fig. 3d shows that the trends are very similar to those corresponding to the 50th percentile, attaining values that on average are about twice those corresponding to the 25th percentile.

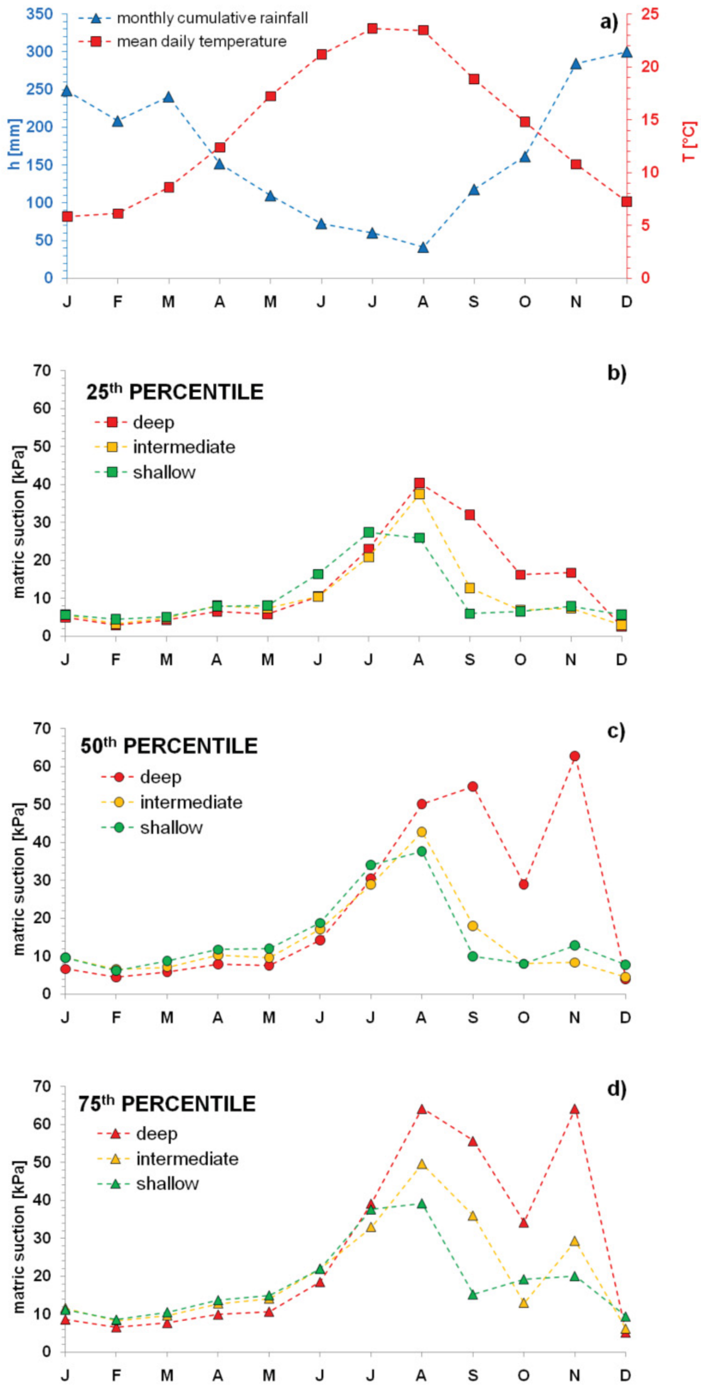

Fig. 3. Field data monitored in Cervinara from January, 2002, to December, 2011: (a) average monthly cumulative rainfall, *h*, and mean daily temperature, *T*; (b) 25th percentile, (c) 50th percentile and (d) 75th percentile values of matric suction monitored at different depths (shallow, intermediate, deep).

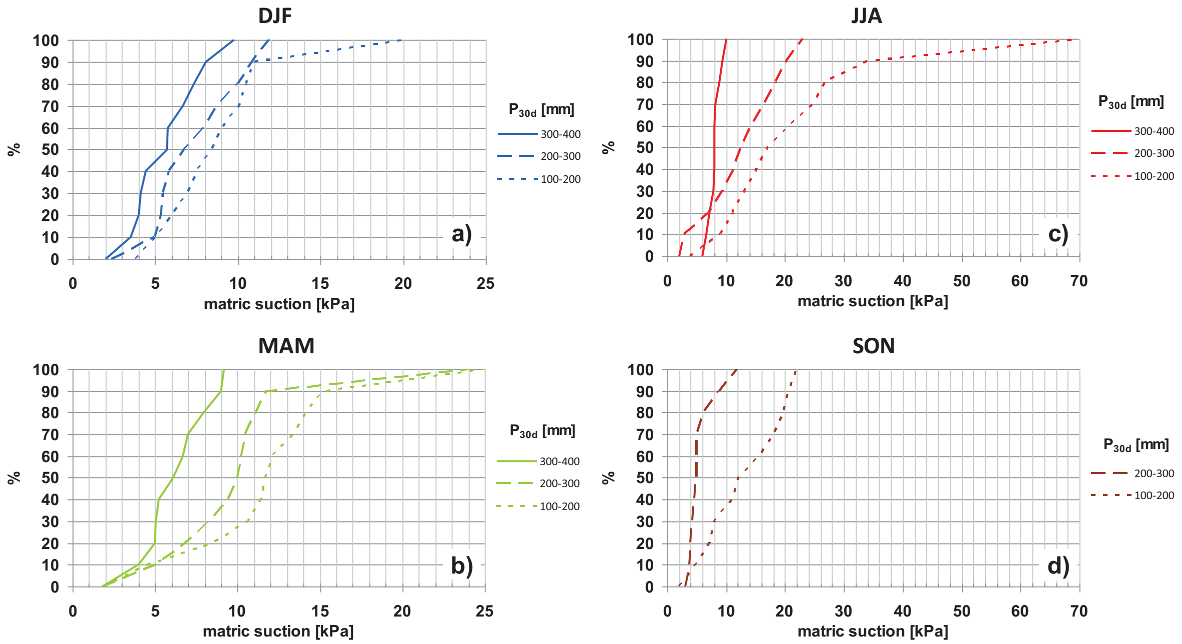

Fig. 4. Cumulative frequency distribution of matric suction measured at shallow depth, at the end of different rainfall monthly cumulative rainfall, $P_{30d,}$during different trimesters: (a) December, January, February (DJF); (b) March, April, May (MAM); (c) June, July, August (JJA); (d) September, October, November (SON).

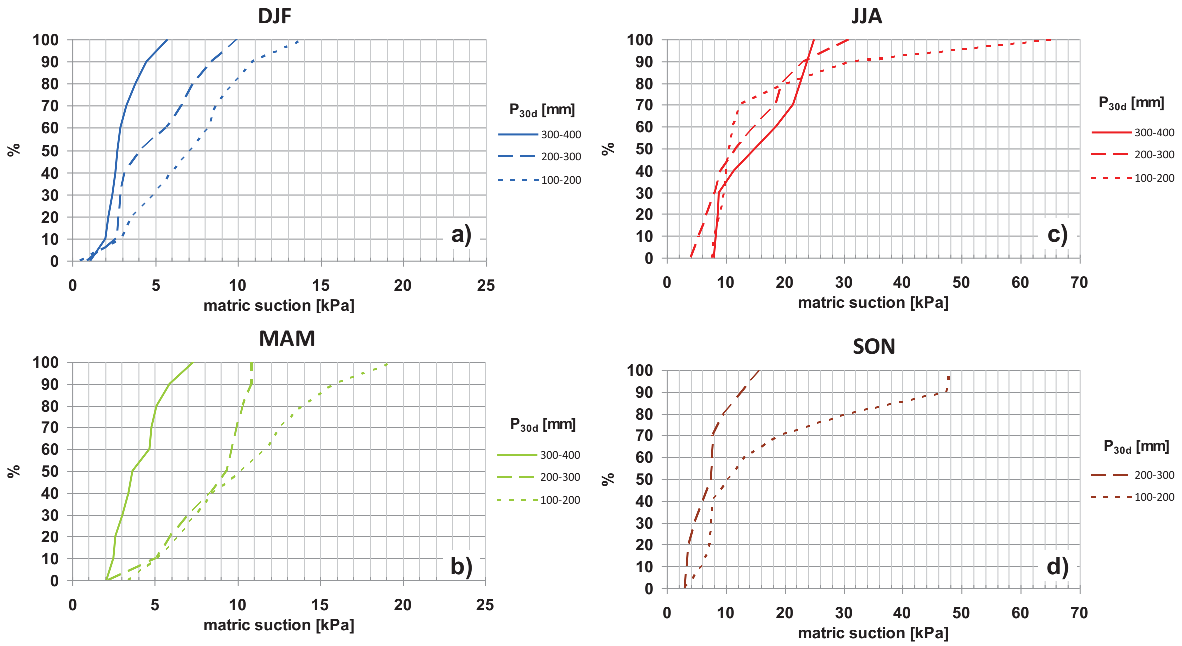

Fig. 5. Cumulative frequency distribution of matric suction measured at intermediate depth, at the end of different rainfall monthly cumulative rainfall, $P_{30d,}$during different trimesters: (a) December, January, February (DJF); (b) March, April, May (MAM); (c) June, July, August (JJA); (d) September, October, November (SON).

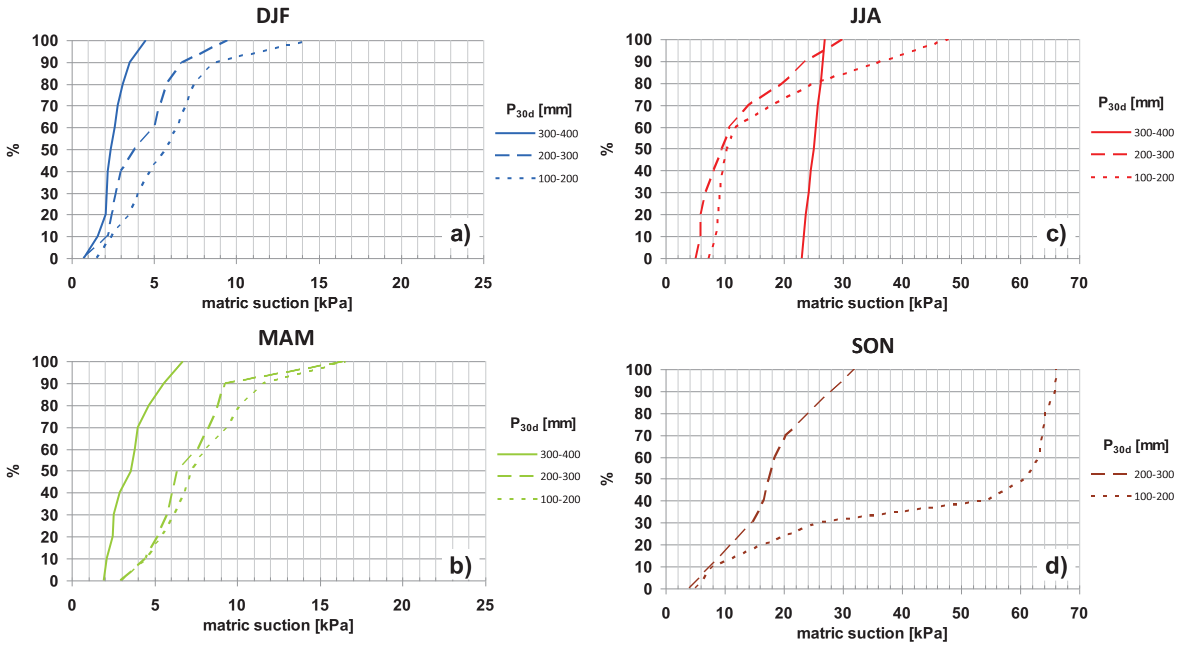

Fig. 6. Cumulative frequency distribution of matric suction measured at deep depth, at the end of different rainfall monthly cumulative rainfall, $P_{30d,}$ during different trimesters: (a) December, January, February (DJF); (b) March, April, May (MAM); (c) June, July, August (JJA); (d) September, October, November (SON).

Table 2. Range of matric suction measured from 2002 to 2011 at shallow, intermediate and deep depth, *z*, during different trimesters: December, January, February (DJF); March, April, May (MAM); June, July, August (JJA); September, October, November (SON).

Depth	Trimester	25th percentile [kPa]	50th percentile [kPa]	75th percentile [kPa]
Shallow (*z* = 0.6 m)	DJF	4-6	6-10	9-11
	MAM	5-8	9-12	11-15
	JJA	16-28	19-38	22-39
	SON	6-8	8-13	15-20
Intermediate (*z* = 0.9-1.3 m)	DJF	3-6	4-10	6-12
	MAM	5-8	7-10	10-14
	JJA	10-38	17-43	22-50
	SON	7-13	8-18	13-36
Deep (*z* = 1.4-2.4 m)	DJF	3-5	4-7	5-9
	MAM	4-7	6-8	8-11
	JJA	11-40	14-50	19-64
	SON	16-32	29-63	34-64

The cumulative frequency distributions of suction grouped by seasons and measured at different depths are plotted in Figs. 4, 5 and 6 as a function of the cumulative precipitation during the antecedent 30 days, P_{30d}. The data include three ranges of P_{30d}: 100-200 mm, 200-300 mm and 300-400 mm. The 300-400 mm range is not reported in the diagram concerning Autumn (SON curve) because of lack of data. A clear reduction in suction can be observed at increasing P_{30d} intervals, with the exception of the Summer season (JJA plot) when the suction values seem to be independent on weather variables. Moreover, a strong seasonal influence on the rainfall effects can be easily recognized looking at the diagrams shown in Fig. 7, which reports the cumulative frequency distribution of suction for each season and for the same P_{30d} range (200-300 mm). At the shallow depths, the lowest values have been measured in Autumn (SON curve in Fig. 7a), while at intermediate and deep depths, the lowest suctions have been always attained in Winter (DJF curve in Fig. 7b and Fig. 7c): as previously noticed, this mostly depends on the delayed effects of infiltration.

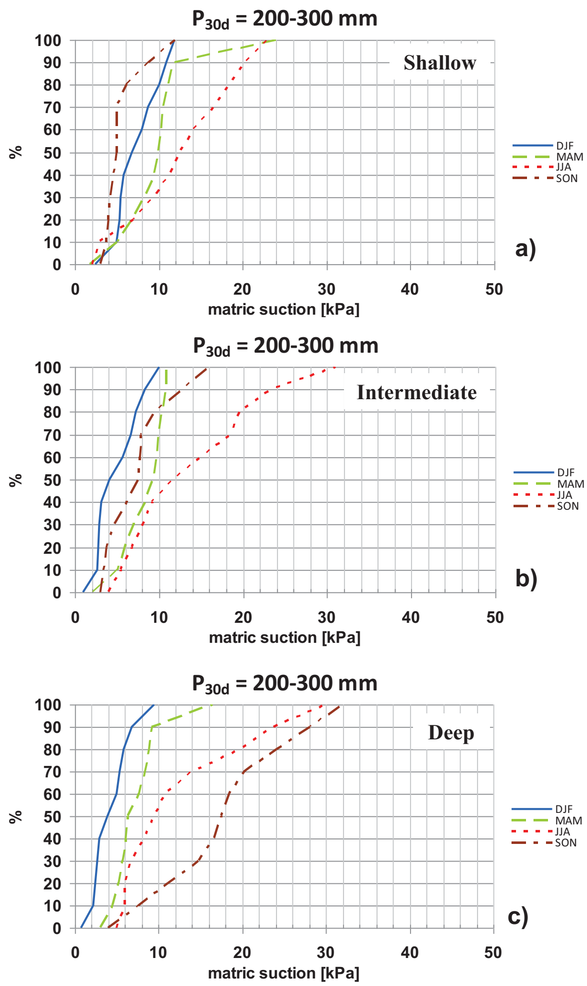

Fig. 7. Cumulative frequency distribution of matric suction measured at shallow (a), intermediate (b) and deep (c) depth from 2002 to 2011 during different trimesters at the end of a 30-day cumulative rainfall P_{30d} = 200-300 mm.

As a matter of fact, the inclination of each curve represents an indication of the homogeneity of suction values: the lower is the slope the higher is the variability associated with the same P_{30d}. It's interesting to note that the inclination tends to increase with P_{30d} (Figs. 4, 5 and 6): probably, the influence of other phenomena (as evapotranspiration) becomes higher during drier periods. At the same time, the suction variability is also related to the effective monthly rainfall distribution. For this reason the P_{7d}/P_{30d} ratio has been adopted, where P_{7d} is the 7-day cumulative rainfall: the higher is P_{7d}/P_{30d} the higher is the fraction of P_{30d} distributed in the last week before the selected date. Fig. 8 shows the relationship between suction measured during Winter for the range P_{30d} = 200-300 mm and the P_{7d}/P_{30d} ratio: as it can be observed, suction is in between 1 and 12 kPafor P_{7d}/P_{30d} ranging between 0 and 0.36. Despite the scattering of data (especially those related to the intermediate layers),quite a clear decreasing trend exists between them at every depth. This then confirms that measured suction is influenced by the latest precipitations.

Such data can be adopted to evaluate the likely starting conditions at the beginning of the rainfall event that on December 16th, 1999, triggered the Cervinaraflowslide. The rainstorm, characterized by 320 mm of rain fallen in two days, was preceded by a monthly (P_{30d}) and weekly (P_{7d}) cumulative precipitation equal respectively to 235 mm and 45 mm. The liable initial conditions could be find out by Fig. 8 that reports suction values measured during the Winter trimester (DJF), for P_{30d} = 200-300 mm, as a function of the P_{7d}/P_{30d} ratio. In the same Fig. 8, two tentative threshold lines are reported, representative of the lowest suction measured at shallow and deep depths: it can be noted that under the above mentioned conditions, the threshold related to the shallow depth is higher than in the deepest layers. Taking into account that in the examined case P_{7d}/P_{30d} is about 0.20, it can be inferred that at the beginning of the triggering storm, initial suctions at shallow and deep depths were respectively at least 5 kPa and 2 kPa. Considering the fitting Water Retention Curve of Fig. 2, the mean initial saturation degree before the triggering rainfall was about 60%. Such a value is very far from full saturation, thus slope failure seems to have been essentially due to the intensity of the triggering event and to the rapid increase of the hydraulic conductivity which favoured rainwater infiltration toward the higher depths where failure should having took place.

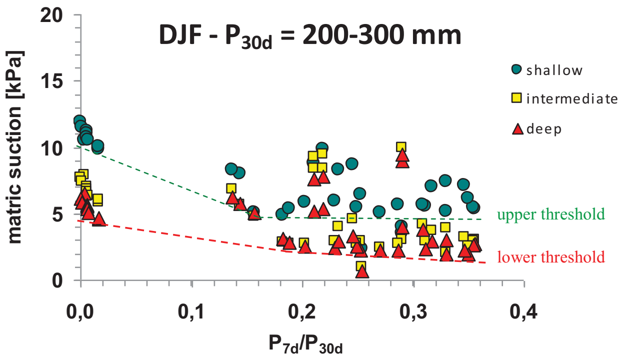

Fig. 8. Matric suction measured from 2002 to 2011 during the trimester DJF at the end of a 30-day cumulative rainfall P_{30d} = 200-300 mm, as a function of the ratio P_{7d}/P_{30d}.

As reminded above, a very similar rainstorm occurred in the same site on November 9th, 2010, characterized by a 2-day cumulative rainfall of 308 mm. Despite of the similarity with the triggering event and antecedent precipitations (P_{7d} = 67 mm, P_{30d} = 345 mm), it did not cause any slope failure. Unfortunately, due to the lack of data related to the 300-400 mm P_{30d} range, it is not possible to estimate the likely initial conditions. Anyway, comparing the curves DJF and SON in Fig. 7, it can be observed that the values of suction attained at the intermediate and higher depths are always higher in Fall than in Winter: in particular, at the highest depths, the median value is more than four times higher. Hence, on November, 2010 the initial mean suction was probably higher than in December, 1999.

4. Conclusions

Field hydrological monitoring is a helpful tool to understand slope response to rainfall events. To this aim, an instrumented monitoring station installed in Cervinara by the research team of the Second University of Naples is providing data about precipitations, soil suction and water content at several locations and depths along the slope. The huge number of data, collected during a long-time monitoring period, allowed to investigate on the effect of precipitations on the seasonal variations of matric suction. One of the main remarks is that similar cumulative rainfalls occurred in different seasons may have different consequences as confirmed by comparing the slope response to two similar rainstorms respectively occurred in December, 1999 and in November, 2010: only the first one triggered the failure.

This is a key issue which once again stresses the importance of the initial conditions on the soil behavior, a point that is not account for by widespread empirical threshold models for timely landslide prediction.

Acknowledgements

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